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Microwave Dielectric Spectroscopy of Ferroelectric Thin Films

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ABSTRACT

We devised a measurement method of microwave dielectric constants of dielectric thin films without applying electrodes. The method uses a rectangular waveguide in which the dielectric thin films prepared on a substrate are filled vertically at the center. The frequency dependence of S-parameter measured by network analyzer enables us to calculate the dielectric constant and loss factor of the films at the microwave region through simulation. We prepared $Ba_{0.6}Sr_{0.4}TiO_3$ thin films on (001) MgO single crystal substrate by pulsed laser deposition (PLD), and determined their dielectric constant and loss factor at ~10GHz using this method.

INTRODUCTION

Nonlinearity of ferroelectric thin films has been studied for applications to tunable microwave devices such as tunable filters, tunable phase shifters, and steerable antennas [1-3]. We need ferroelectric thin films with high tunability and low loss at microwave frequencies to develop tunable devices of good properties. The tunability of ferroelectric thin films generally increases in proportion to their dielectric constant. Therefore, it is indispensable to measure accurately dielectric properties of ferroelectric thin films at the frequencies that tunable devices are operated. The investigation has been usually made through measuring the capacitance of an interdigital capacitor on ferroelectric thin films. The precise analysis of this method needs an appropriate model that can extract the capacitance of ferroelectric thin films from the total one [4]. In addition, we cannot utilize the ferroelectric thin films for the device fabrication after the measurement.

In this study, we devised a simple method that can measure microwave dielectric properties of ferroelectric thin films without applying electrodes. Because the method does not damage ferroelectric thin films, it is possible to fabricate tunable devices directly on them after the measurement of their dielectric properties. Using this method, we investigated the dielectric constant and loss factor of $Ba_{0.6}Sr_{0.4}TiO_3$ (BST) thin films on (001) MgO single crystal substrate prepared by pulsed laser deposition (PLD).

MODEL: PARTIALLY FILLED WAVEGUIDE

When we investigate dielectric properties of a sample in a waveguide, we usually use the sample with which the cross section of the waveguide is fully filled. However, we cannot use such a structure for ferroelectric thin films that are very thin and their dielectric constant are very high. Instead, it is desirable to use the partially filled waveguide that can provide increased propagation of microwaves. In this case, as shown in figure 1, the sample is filled at the center of the waveguide to maximize the interaction with the electric field of propagated waves and to enhance the resolution of the measurement.

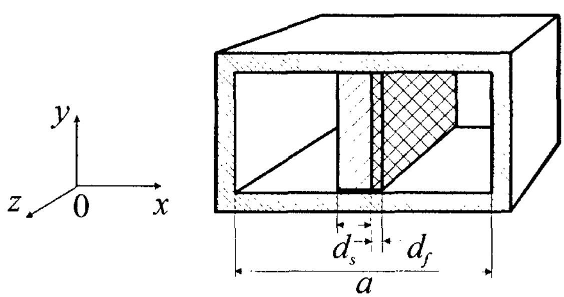

Figure 1. The scheme of partially filled waveguide.

The comparison between measured and calculated S-parameters at the situation shown as figure 1 enables us to find the dielectric constant and loss factor of the ferroelectric thin film. To find calculated S-parameters, we need to solve the electromagnetic field problem of the partially filled waveguide. From the calculated equations on the electromagnetic field problem of the structure, we can find the dielectric constant and loss factor of ferroelectric thin films at a certain frequency. However, the accuracy of the one-point technique is strongly affected by the accidental errors [6]. We can enhance the accuracy by using calculated S-parameters provided the dielectric constant and loss factor of ferroelectric thin films are constant at the frequency region concerned. If a dielectric constant and loss factor of the ferroelectric thin film are given, we can calculate S-parameters of the partially filled waveguide. We can finally find the dielectric constant and loss factor of ferroelectric thin films by minimize errors between measured and calculated S-parameters through several iterations.

Electromagnetic field calculation of the partially filled waveguide

When the substrate with a ferroelectric thin film is situated at the center of the waveguide as shown in figure 1, TE^z or TM^z mode alone cannot satisfy the boundary conditions of the partially filled waveguide, but combinations of TE^z and TM^z modes can satisfy them.

If we use these hybrid modes for the calculation of partially filled waveguide, the electromagnetic field problem can be solved as follows: [5]

$$\beta_s \tan\left(\beta_s \frac{a}{2} - \varphi_s\right) = \beta_f \tan\left(\beta_f \frac{a}{2} - \varphi_f\right)$$

$$\varphi_s = \beta_s\left(\frac{a}{2} - d_s\right) + \tan^{-1}\left[\frac{\beta}{\beta_s}\cot\left\{\beta\left(\frac{a}{2} - d_s\right)\right\}\right]$$

$$\varphi_f = \beta_f\left(\frac{a}{2} + d_f\right) + \tan^{-1}\left[\frac{\beta}{\beta_f}\cot\left\{\beta\left(\frac{a}{2} + d_f\right)\right\}\right]$$

$$\beta = \sqrt{k_0^2 - \gamma^2}\,,\quad \beta_s = \sqrt{\varepsilon_s k_0^2 - \gamma^2}\,,\quad \beta_f = \sqrt{\varepsilon_f k_0^2 - \gamma^2}$$

where a is the width of waveguide, d_s is the thickness of substrate, d_f is the thickness of ferroelectric thin films. Also, β, β_s, β_f are transverse wave numbers in the media of air, substrate, and ferroelectric thin films, respectively, and γ is the propagation constant.

EXPERIMENT

$Ba_{0.6}Sr_{0.4}TiO_3$ thin films were deposited on $22\times10\times0.5$ mm^3 (001) MgO single crystal substrate at 730°C under 50mTorr oxygen using KrF excimer laser. Thickness of the films is 840nm. We filled the center of a rectangular waveguide (width a =22.86mm, height b =10.16mm) partially with the MgO substrate deposited with a BST thin film (see figure 1.) and measured S-parameters by a network analyzer (HP-8510C) at the frequencies of 8.2-12.4GHz. Because we need to know the microwave dielectric properties of MgO substrate for the analysis of ferroelectric thin films, we also measured S-parameters of MgO substrate without a BST thin film in the same way. Before measuring the S-parameters, we calibrated the network analyzer with a calibration kit for a rectangular waveguide (WR-90) to remove attenuations at the adaptor for coaxial to rectangular waveguide.

RESULTS AND DISCUSSION

We found the dielectric constant ε and loss factor $\tan\delta$ of ferroelectric thin films using a nonlinear least square curve fitting technique between measured and calculated S-parameters as follows:

$$\min \sum_k \sigma_k \left[S_k^{meas} - S(f_k, \varepsilon, \tan\delta)\right]^2$$

where σ_k is a weight function, S_k^{meas} is the measured S-parameter at frequency f_k, and $S(f_k, \varepsilon, \tan\delta)$ is the calculated value of S-parameter at the same frequency.

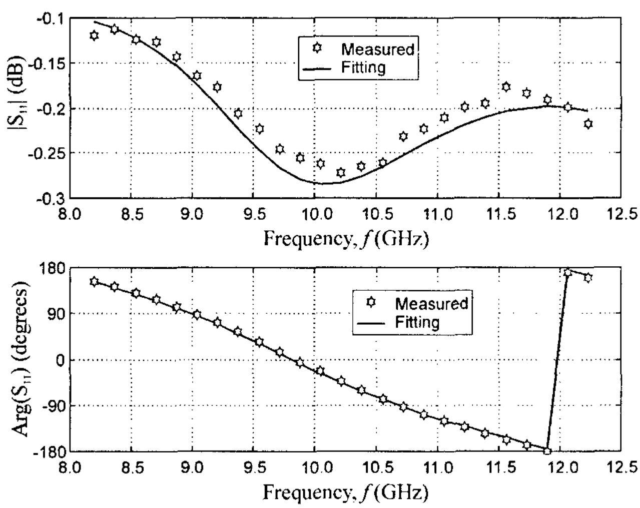

Figure 2. Comparison between measured and calculated S-parameters of ferroelectric thin films deposited on MgO substrate in the partially filled waveguide.

Figure 2 shows measured S-parameters and calculated ones that minimize errors between them, which are well matched each other. We found that the dielectric constant (ε) and loss factor ($\tan\delta$) of ferroelectric thin films were 450 and 0.05 at frequencies of 8.2-12.4GHz, respectively. In this measurement, we used microwave properties of MgO substrate measured with the same method, ant its dielectric constant and tangent loss were 9.91 and 0.0004, respectively, at the same frequency region. If we compare these values of the MgO substrate with those reported previously [7], there exists small difference for the dielectric constant. However, the loss factor measured with our method was slightly larger than the reported value. The loss may include the contributions from the waveguide and/or the non-ideal substrate. However, the loss factors of thin films determined by our method do not include such factors because they could be removed by using the loss factor of the MgO substrate that includes them.

CONCLUSIONS

We investigated microwave dielectric properties of $Ba_{0.6}Sr_{0.4}TiO_3$ thin films on (001) MgO single crystal substrate deposited by pulsed laser deposition (PLD) with no electrodes. The analysis was made using a partially filled waveguide through comparing between measured S-parameter with network analyzer and calculated ones at the same situation. From the method, we found that their dielectric constant was 450 and tangent loss was 0.05 at the frequencies of 8.2-12.4GHz.

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